5.6 NUCLEAR CRITICALITY SAFETY CONTROL PRINCIPLES AND METHODS. This section provides nuclear criticality safety principles, practices, and control methods to be used for prevention of criticality accidents. An assessment of a design should be made as early as practical to determine if the potential for a criticality accident exists.

Nuclear criticality safety evaluations shall demonstrate that the conservatism principle is met for all credible cases. The demonstration should include logical explanations of how design features, controls, and planned responses to events are conservative, simple, and consistent, and how they encompass all credible scenarios. Where practical, the demonstration should also include numeric comparisons between measurable parameters affecting criticality safety. Conservative assumptions involving these parameters increase the calculated *effective multiplication factor* compared to actual conditions or non-conservative assumptions. However, *conservatism* is different from setting a minimum safety margin such as requiring that the calculated *effective multiplication factor* not exceed 0.95 after the occurrence of any single *contingency*. Specific items to be considered in making these comparisons include uncertainties in chemical and isotopic compositions, manufacturing tolerances, minor deviations, and other random variations in critical experiments as well as in all actual and postulated situations to be evaluated for criticality safety. For example, when performing criticality safety calculations for slurries of uranium oxide, it is customary to assume that the uranium is at the maximum enrichment permitted in the facility, the oxide is at the most reactive credible density, and water fills all voids resulting in maximum reactivity. It is also customary to perform a parametric search to find the solid/liquid ratio that yields highest k_{eff} and use that ratio to derive controls. However, to be in accordance with the conservatism principle, it is not necessary that each simplifying assumption be shown to increase calculated k_{eff}. It is only necessary that the overall result of interpretations of data, assumptions, approximations, and simplifications (as either inputs to, or outputs from, evaluations, analyses, and supporting documents) be conservative, and that this is clearly documented. That is, it is acceptable if some individual simplifying assumptions decrease reactivity, or if the effect on reactivity is indeterminate as long as the documentation makes it clear that, overall, the actual margin of safety meets or exceeds the minimum margin required. Also, it is acceptable if the actual safety margin is quite different for different cases as long as there is a clear rationale for the trend and unless the degree of conservatism is excessive. Excessive conservatism is any approximation or combination thereof that results in an excessive safety margin and thus needlessly hinders the mission of the facility or usurps resources. Details concerning nuclear criticality safety evaluations can be found in DOE-STD-3007-93, "Guidelines for Preparing Criticality Safety Evaluations at Department of Energy non-Reactor Nuclear Facilities," section 2.3.2.4 of this standard.

Geometry of single objects of fissionable material or shape and size of the fissionable material inside containers, and assumptions about or changes thereto, often play a dominant role in conservatism. Fortunately, in almost all cases of singular geometries, circular geometries such as spheres and cylinders with height approximately equal to diameter are more reactive than other geometries for the same volume and contents. Also, an out-of-round or dented cylinder typically will be less reactive than a perfectly circular one. A typical conservative approximation is to model a fissionable material mixture whose shape is uncontrolled as a sphere because a sphere has the lowest neutron leakage ratio and is thus the most reactive shape in practically all cases. (Refer to E. D. Clayton's "Anomalies of Nuclear Criticality," (section 2.3.2.4 of this standard) for exceptions to this and other conservative simplifications.) This example achieves two desirable goals: first, it encompasses all possible shapes, and second, it greatly simplifies the calculations. However, not every item increasing size or changing shape to increase *reactivity* qualifies as a conservatism. For example, increasing the inside diameter of a cylindrical dissolver in a calculational model to allow for corrosion over the dissolver's expected service life is not in itself a conservatism, because at some point the inside diameter may achieve the value used in the evaluation. To be conservative, the engineering calculation that yielded the corrosion allowance shall also include all associated uncertainties in projected usage of the dissolver.

Conservatism is closely linked with other safety principles and practical considerations such as the need for consistency and simplicity in applying criticality safety. For example, rounding down mass limits on fissionable material quantities to a set of consistent, easy to remember values creates many conservative simplifications. However, adopting a uniform set of limits may cause the degree of conservatism to vary widely from place to place in the facility; exceptions to rote consistency may be warranted to avoid excessive conservatism. One should strive for a practical balance between excess conservatism arising from overly simplified, too-consistent limits and confusion that may arise from having too many exceptions. Worker knowledge should be continually tested, and operational mistakes should be reviewed to determine if the set of limits is too complex or whether conservatism can be safely relaxed.

5.6.1 Double-Contingency Principle (Application). Criticality prevention shall be based upon the double-contingency principle of DOE Order 420.1, Section 4.3, which states:

> Process designs [and storage areas] shall incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes in process conditions [contingencies] before a criticality accident is possible. Protection [or defenses against the two contingencies] shall be provided by either (i) the control of two independent process [nuclear] parameters (which is the preferred approach, when practical, to prevent common-mode [and common-cause] failure), or (ii) a system of multiple controls on a single process [nuclear] parameter. The number of controls required upon a single controlled process parameter shall be based upon control reliability and any features that mitigate the consequences of control failure. In all cases, no single credible event or failure shall result in the potential for a criticality accident, except as referenced in the paragraph that follows.
>
> An exception to the application of double contingency, where single contingency operations are permissible, is presented in paragraph 5.1 of ANSI/ANS-8.10-1983,R88. This exception applies to operations with shielding and confinement (e.g., hot cells or other shielded facilities).
>
> Double contingency shall be demonstrated by documented evaluations.

5.6.1.1 Requirements of contingencies. Contingencies shall be independent and not be the result of common-cause failures. The collective judgment of operating and criticality safety staff is required in determining whether two events are related and consequently whether they actually represent two contingencies or a single contingency. For example, exceeding storage limits and then flooding an area would constitute two independent events; however, fire followed by flooding from an automatic sprinkler system would be considered a single event.

The following guidelines are for selecting contingencies and deriving appropriately conservative calculational models that bound the resultant assumed conditions.

1. Develop and justify a set of contingencies to evaluate for criticality safety.

a. Use Safety Analysis Reports or other guidance documents describing contingencies, e.g., maximum credible flood depth in the facility. Justification may consist of references to other authoritative documents.

b. If existing guidance is not adequate, develop and justify the magnitude of each type of contingency and the resultant effects on nuclear criticality safety. E.g., if the maximum credible flood depth is two feet above floor level in a given facility, objects of or containing fissionable material located more than two feet off the floor may not be flooded. However, account for any incidental moderation and reflection of other objects that may occur because of the contingency.

c. Be consistent, and explain apparent inconsistencies in the contingency selection and justification logic.

d. Document the nature of, and justification for, contingencies and supplemental explanations.

2. Demonstrate subcriticality for the contingencies selected for evaluation using the Double-Contingency Principle.

3. Unless it would be a futile exercise, force the evaluation of the contingency or subset of contingencies to maximize k_{eff} by adopting a very conservative calculational or handbook model.

a. For example, if flooding of a large container (e.g., a glovebox) is the contingency, assume that the water and fissionable material form a sphere that becomes optimally moderated and fully reflected by water.

b. It may be necessary to refer to handbooks or perform a set of parametric calculations to determine optimum moderation. If necessary, parametric studies using simple models are relatively easy to set up, inexpensive, and easy to check.

c. While this approach may yield restrictive limits, contingency selection, modelling, and interpretation errors are less likely than when using complex models.

d. If the limits from the first cut effort by operating and criticality safety staff are not overly restrictive and are in harmony with other criticality safety limits, adopt them.

4. If a very conservative evaluation produces (or it is reasonable to expect that one would produce) unacceptably high k_{eff}s for the desired fissionable mass or other parameters, next consider physical and chemical factors or passive barriers that realistically prevent the most reactive state from occurring.

a. Justify the assumed revision of the effects of the contingency on the fissionable material and associated material as necessary.

b. It is prudent to perform parametric studies to determine the relative importance of an assumption, e.g., determine k_{eff}s for a range of moderation including optimum moderation and the perceived natural limit due to chemistry or physics of the situation versus the benefit of taking advantage of the phenomenon or taking credit for barriers.

5. It is even more important to carefully consider the reliability of assumptions and barriers that are relied upon to reduce k_{eff} to a safe value in evaluating contingencies. This is illustrated by continuing the glovebox example. If the glovebox contains only finished fuel pellets of stable, high density oxide, the effect of the contingency of breaking a water line inside the glovebox may be interpreted quite differently than if the glovebox contains less stable materials. For typical gloveboxes, it is highly unlikely that such a line break will cause a flow rate sufficient to disturb fuel pellets.

   a. Therefore, the dimensions of the fuel in the calculational model may be changed to approximate the dimensions of a group of pellet trays, a much less reactive shape than a sphere.

   b. Also, the degree of moderation used in the calculations may be the relatively low moderation ratio that would result from water filling the small gaps between rows of pellets.

   c. It may reduce k_{eff} significantly further to include dimensions and orientation of the pellets or to approximate their shape in the model. However, modeling small items, besides making the model more complex, has other drawbacks; some codes and cross sections produce non-conservatively low k_{eff}s unless flux- and volume-weighted cross sections are generated and used correctly.

   d. Additionally, because it is not credible to flood the entire building and because gloveboxes are typically a few feet above the floor, it may be acceptable to assume that the underside of the array of pellet trays is only minimally reflected.

   e. This combination of assumptions exemplifies the concept of minimum conservatism and yields maximum limits for a given contingency scenario. HOWEVER, CAUTION IS INDICATED AS DISCUSSED BELOW!

6. Another contingency scenario involving minimum conservatism for the same glovebox could be stacking trays of pellets (against the rules) to create a more reactive geometry while assuming essentially no moderation in the calculational model.

7. The caveat in using calculational models with minimum conservatism, especially when some assumptions depend upon complying with administrative controls, is that one or more assumptions used to create the model may become invalid concurrently. This is illustrated by considering the glovebox example further.

   a. Suppose the glovebox normally contains acid, and that, because of the flooding, the lid to the acid bottle comes off, the acid mixes with the water, and the mixture dissolves the pellets partially.

   b. Or suppose that personnel store items under gloveboxes (there being no rule preventing this); thus, in the flooding scenario, reflection may more closely approximate full water reflection on all sides. Even if criticality safety establishes a rule not to store items under gloveboxes, that is a convenient place to store items, and it is likely that the rule is unenforceable.

8. Continuing the example, it is less likely that the rule mentioned above against stacking pellet trays will be broken.

   a. This is because only trained fissionable materials handlers have access to the insides of gloveboxes.

   b. Nevertheless, a combination of circumstances may occur to cause two seemingly independent contingencies to occur simultaneously.

   c. For example, a worker maneuvering a tray of pellets over a group of pellet trays may break a water line inside the glovebox and, being distracted, place the one tray down on the others while trying to close the shut-off valve that is, unfortunately, stuck.

9. Less conservatism in selecting contingencies and their effects requires more in-depth study and calculations, and may result in necessitating other limits and requirements that *in toto* may be just as restrictive as the low limit resulting from applying more conservatism.

10. Less conservatism may result in training becoming more complicated, and it may be necessary to audit for criticality safety more frequently and more closely to ensure that subtle misunderstandings and changes to equipment or the facility do not invalidate assumptions made in the evaluation. There may be no real benefit to the organization as a whole by producing a larger limit based on less conservative interpretations of contingency scenarios.

11. Therefore, insofar as practical, use simple, conservative models to address each contingency, and consider other alternatives before reducing conservatism to a minimum. These include establishing physical barriers or administrative controls to mitigate the effects of contingencies.

12. Criticality safety personnel must confer with cognizant personnel to determine the reasonableness of models and the effect that excess or even moderate conservatism may have. However, experienced personnel can attest to actual situations during contingencies in which criticality did not occur because of conservatism in the calculational model and resultant limits.

13. Conversely, contingencies must also be considered in the light of total safety. The consequences of accidental criticality for a given contingency or subset of contingencies may be overshadowed by other consequences associated with the events.

   a. In particular, there are some DOE facilities that cannot be expected to survive certain design basis accidents or design basis events.

   b. For example, if the non-criticality accident consequences of a contingency scenario would include fatality to all personnel in the area who might receive significant doses from a criticality, preventing criticality for that scenario is moot.

c. Nevertheless, insofar as is practical, criticality safety controls should be established to protect rescue, fire-fighting, and other personnel from undue radiological exposure and contamination resulting from a criticality accident while they are involved in mitigating or recovering from contingencies.

5.6.1.2 Scope of contingencies. Single events that are beyond Design Basis Accidents (DBAs) are outside the scope of double-contingency principle requirements.

5.6.1.3 Nuclear criticality safety analyses. A double-contingency analysis shall be included as part of the Nuclear Criticality Safety Analysis (NCSA) for processes, pieces of equipment, storage, and transportation involving fissionable material. Summaries of individual double-contingency analyses for each facility shall be compiled and summarized as part of the facility Safety Analysis Report as required by reference 2.1.12. Additional guidance on preparation of a double-contingency analysis is provided in section 5.7.8.1.

5.6.1.4 Contingency controls reliability. Contingency barriers (controls) are engineered safety features, parameter limits, and other administrative controls that render a contingency unlikely or mitigate its effects. These barriers should be made highly reliable such that each contingency, including credit for mitigation, should have an estimated return period of less than 10^{-2}/yr. Engineering judgment may be the basis of making a determination that a control is highly reliable. Guidance on failure probabilities of contingency barriers (controls) that are acceptable are provided in references 2.2.2.8 and 2.3.1.16. In addition, efforts should be directed toward maintaining the estimated recurrence interval for a criticality accident to a value less frequent than once per 10,000 years at any given nonreactor nuclear facility.

5.6.1.5 Contingency control margin of subcriticality. No single contingency shall result in k_{eff} exceeding the upper subcritical limit as discussed in sections 5.8.4 and 5.8.5 or as developed from directly applicable critical or subcritical experimental measurements. Nuclear parameters that are not controlled to some limit shall be assumed to take the most reactive credible values when determining whether k_{eff} could exceed the upper safety limit.

5.6.1.6 Treatment of dependent contingencies. If contingency barriers are not independent, common causes shall be identified, such as common power supplies, common methods of calibration, common components, and steps taken to remove common-cause failure dependencies to the extent practical. If common-cause failures of contingency barriers cannot be eliminated, the common-cause may be acceptable if the common features can be shown to fail in a manner that maintains the minimum margin of subcriticality for any given contingency. Alternatively, common-cause failures of contingency barriers may be acceptable if their frequency is less than 10^{-6}/year.

5.6.1.7 Identification of engineered or administrative controls. Each passive engineered control, active engineered control, or administrative control (see sections 5.7.5.1.1 - 5.7.5.1.3 below) associated with a contingency barrier shall be conspicuously and prominently identified in Operational Safety Requirements or Technical Safety Requirements (passive engineered controls), or operating procedures or Technical Safety Requirements (active engineered and administrative controls). Engineering drawings should also identify such contingency barriers. Each contingency barrier by physical means should be based on safety class systems.

5.6.1.8 Exception from double-contingency principle. Application of the double-contingency principle shall not be required for contingencies that are highly unlikely. Highly unlikely is defined as an estimated annual frequency of occurrence of less than 10^{-4}/yr. That is, from an analysis standpoint, the potential for criticality as a result of a single contingency is acceptable as long as the estimated annual occurrence of that contingency is less than 10^{-4}/yr. Examples of such events are (1) earthquake in spent fuel storage basin, and (2) evaporation in a tank containing a solution of fissionable material under concentration control. If there is no substantive basis for estimating that a potential accident scenario is highly unlikely, whether by probabilistic assessment, engineering judgment, or data, then the double-contingency principle shall be applied. However, see section 5.6.1.11 below.

5.6.1.9 Preferred hierarchy of controls. To the extent practicable, contingency barriers should employ passive engineered controls over active engineered controls over administrative controls.

5.6.1.10 Avoidance of administrative controls. All reasonable efforts shall be directed toward avoiding the use of administrative controls only (see section 5.7.5.1.3 below) as the sole barrier to a criticality accident.

5.6.1.11 Exemption from double-contingency principle. If "double-contingency" protection cannot be provided, an exemption from DOE Order 420.1, Section 4.3 shall be obtained.

5.6.2 General Nuclear Criticality Safety Control Principles and Practices. The following are principles and practices used in the control of nuclear parameters.

5.6.2.1 Safety assurance. Nuclear criticality safety shall not be compromised for the sake of expediency, production, or economic pressure.

5.6.2.2 Potential criticality assessment. An assessment of a facility or equipment design should be made as early as practical to determine if the potential for a criticality accident exists. When such potential exists, facility and equipment designs shall meet applicable DOE Orders, ANSI/ANS standards, and other regulations related to nuclear criticality safety.

5.6.2.3 Burn-up credit. Criticality safety evaluations (calculations) for undissolved reactor fuels and targets shall be based on beginning-of-life (pre-irradiation) fissionable material concentrations and enrichments except when irradiation increases fuel reactivity or specific power histories and burn-up is technically demonstrated.

5.6.2.4 Storage. Storage of fissionable materials should be consistent with the guidance provided in sections 2.3.1.5, 2.3.1.6, 2.3.1.8, 2.3.1.10, and 2.3.1.13, unless specific nuclear criticality safety evaluations have been performed.

5.6.2.5 Special actinide element evaluations. Criticality safety control of special actinide elements shall be consistent with section 2.3.1.9, unless specific validated and verified nuclear criticality safety evaluations have been performed. Additional information is presented in "Criticality and Fissionability Properties of Selected Actinide Nuclides" (section 2.3.2.8 of this standard).

5.6.2.6 Subcritical neutron multiplication measurements. Subcritical neutron multiplication measurements shall be consistent with guidance in section 2.3.1.4.

5.6.2.7 Criticality accident alarm systems. The implementation and functioning of, and employee familiarization with, criticality accident alarm systems shall be consistent with sections 2.1.13 and 5.4.

5.6.2.8 Process and equipment design. Design of processes or equipment should make proper operation convenient and misoperation either inconvenient or impossible.

5.6.2.9 Process analysis. Before beginning an operation involving fissionable materials, or changing an existing operation, it shall be determined that the entire process will be subcritical under both normal and credible abnormal operating conditions. Care shall be exercised to determine those conditions that result in the maximum effective neutron multiplication factor.

5.6.2.10 Bases for subcriticality. The basis for establishing subcriticality shall be identified for all significant conditions at each step in the process. In the case of established facilities or operations, this may consist of references to existing nuclear criticality safety analyses (NCSAs).

5.6.2.11 Operating procedures. Process operating procedures shall incorporate safety margins to protect against uncertainties in process variables and against a limit being accidentally exceeded.

5.6.2.12 Exempt quantities of fissionable materials. Threshold quantities of fissionable materials that require criticality safety control shall be justified and documented by the Criticality Safety Organization for each installation, site, and/or facility.

5.6.3 Nuclear Parameters Important to Nuclear Criticality Safety and Their Control. Control of one or more of the following nuclear parameters shall be incorporated into the design, operation, and administration of a fissionable material facility to the extent necessary to ensure conformance to the principles set forth in sections 5.6.4 and 5.6.1. More detailed information about the control of these nuclear parameters may be found in section 5.7.

5.6.3.1 Geometry control. Geometry control is the limitation of dimension and geometry to provide inherently "geometrically safe" or "geometrically favorable" containers, vessels, drains, and sumps for fissionable materials.

5.6.3.1.1 Equipment design reliance. Where practical, reliance should be placed on equipment design in which dimensions are limited (geometry control). Full advantage may be taken of any nuclear characteristics of the process materials providing that their presence has been verified and is monitored for continuing presence. All dimensions and nuclear properties upon which reliance is placed shall be verified prior to beginning operation, at appropriate intervals, and if significant changes are made or discovered.[24]

5.6.3.1.2 Fissile solution transfers. Where fissile solution transfer between geometrically favorable and geometrically unfavorable vessels is possible, at least one passive or two active means of control such as block valves or pipe blanks (in addition to administrative means of control) shall be used to prevent inadvertent transfers.

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[24]ANSI/ANS-8.1-1983,R88, "Nuclear Criticality Safety in Operations with Fissionable materials Outside Reactors," paragraph 4.2.3.

5.6.3.1.3 Allowances with geometry control. When using geometry control, allowances shall be made for corrosion, distortion, erosion, and manufacturing tolerances. If distortion is a potential problem, steps shall be taken to prevent it such as pressure relief valves, internal stay-bolts, rupture discs, heavier wall thickness, external bracing, and the use of more inherently stable geometries. In addition, subcriticality shall be based on the worst credible geometry conditions.

5.6.3.1.4 Control monitoring. Nuclear criticality safety controls shall include provisions for periodic evaluation by an inspection program, use of corrosion specimens, or other techniques, if credible corrosion or erosion could change the geometry (or thickness) in a system that depends on geometry (or thickness) for nuclear criticality safety.

5.6.3.1.5 Thermal insulation concerns. The design of heating or cooling jackets shall include consideration of leaks of fissionable material into such jackets. Appropriate measures shall be taken to preclude accumulations of fissionable material in jackets such that a criticality accident is possible.

5.6.3.1.6 Sump designs. Sumps shall be designed such that nuclear criticality safety is ensured if a credible mechanism exists for accumulating fissionable material in the sump.

5.6.3.1.7 Floor drains. Where applicable, floor drains shall be designed to preclude the accumulation of fissionable material in traps and piping that could cause a criticality accident.

5.6.3.1.8 Inadvertent transfers. Process systems shall be designed to prevent the carryover of fissionable material capable of causing a criticality accident from geometrically safe/favorable portions of a facility to other areas not having geometry control.

5.6.3.1.9 Backflow prevention. A system of positive control and backflow prevention, such as air gaps, shall be used to prevent the inadvertent transfer of fissionable material capable of causing a criticality accident from geometrically safe/favorable vessels to unsafe vessels.

5.6.3.2 Spacing (interaction) control. Spacing control is used to restrict neutron interaction between and among various units, vessels, containers, and accumulations of fissionable materials to prevent nuclear criticality. It may include controls on spacing, arrangement, and shielding (neutronic isolation). Spacing provided by passive engineered controls is preferred over spacing provided by active engineered controls which, in turn, is preferred over spacing provided by administrative controls. Use of other than passive engineering features to provide spacing should be fully justified.

5.6.3.2.1 Storage and transfer. Individual items of equipment and containers holding fissionable materials, when arranged in a group, in storage, or when being transferred within a nuclear facility or between facilities onsite, shall be spaced so that the entire array is subcritical for all conditions that affect or might affect the nuclear facility or site. Movement of material under credible in-facility and onsite accident conditions shall be considered.

5.6.3.2.2 Storage rack integrity. Storage racks shall be designed to maintain their integrity during and following a design basis earthquake and the design basis accidents they are required to withstand.

5.6.3.3 *Neutron absorber (poison) control. For the purpose of this standard,* a neutron poison is any material intentionally added to an operation or to a piece of equipment for maintaining subcriticality. Control using solid neutron poisons incorporated into passive engineered controls such that the neutron poisons are protected from dissolution or dispersion is preferable to soluble neutron poisons controlled by active engineered controls. That form of control is preferable to concentration of soluble neutron poisons controlled by administrative controls. When poisons are specified, use of other than solid neutron poisons incorporated into protected passive engineered controls shall be fully justified, including a description of the need for a neutron poison (solid or liquid), its distribution, concentration, and permanence.

5.6.3.3.1 Suitability. Neutron poisons, such as cadmium, boron, and gadolinium, may be used to make equipment and processes safe, provided measured data or validated computational results confirm the effectiveness of the neutron poison and ensure its presence and reliability.

5.6.3.3.2 Raschig rings. The use of borosilicate-glass Raschig rings for packed vessels shall be consistent with the applicable document in section 2.3.1.3. The use of borosilicate-glass Raschig rings for applications other than packed vessels shall be based on a documented NCSA.

5.6.3.3.3 Representative samples. Use of representative samples, such as corrosion coupons, to verify the continued presence of a fixed poison shall require approved documentation that demonstrates that the samples actually represent the poison system.

5.6.3.3.4 Minimum soluble poison concentration. The minimum soluble poison concentration shall be at least 100% of the poison concentration required to ensure the validated and documented subcritical limit under any contingency.

5.6.3.3.5 Soluble poison measurements. Two independent methods of determining the operating concentration of a soluble poison shall be provided to confirm that the poison concentration limit is satisfied.

5.6.3.3.6 *Soluble poison monitoring. The* presence of soluble poison shall be monitored at a frequency that provides for automatic or operator initiated protective action in the event of process upsets.

5.6.3.4 Concentration (density) control. Concentration and density are different concepts -- concentration connotes a fissionable material solution, molten salts, or a fine dispersion in another media; density connotes only one medium, the fissionable material.

Concentration control is typically used to provide restrictions on the permitted concentrations of fissionable material dissolved or dispersed in another medium. For example, density control is meaningless for low enriched uranium metal and many compounds while concentration control may be vital. Sources of weaknesses of concentration controls are: evaporation, precipitation, phase change (organic to aqueous phase and vice versa), fire in an organic phase, flocculation, plate-out, centrifuging suspended solids, non-representative sampling, *solids building up on filters, and not* sampling for all fissile nuclides present.

Density controls are generally applied to restrictions on fissionable material mass-to-volume values of powders, metal chips, machine turnings, etc. On occasion, density restrictions are applied to allowable chemical compounds or physical states for fissionable materials at particular process stages, work stations, and storage areas; and restrictions on the allowed fissionable mass per unit area (such as a floor or the bottom of a glovebox).

5.6.3.4.1 Process changes in density. If the determination of a concentration (density) limit assumes fissionable material in solution, it shall be shown that the change to a more reactive state due to precipitation or transfer to a second phase is not credible before the change is eliminated from consideration as a contingency.

5.6.3.5 Moderation control. Moderation controls are used to provide restrictions on the allowed range of moderating material relative to fissionable material in moderator/fissionable mixtures or solutions (typically H/X, D/X, Be/X, C/X atom ratio) or on the total amount of moderating materials allowed. Such controls may be applied to ensure that the fissionable material remains dispersed and dilute. In other cases, the controls may be applied to ensure that the fissionable material remains dry.

5.6.3.5.1 Monitoring neutron moderation. For operations in which nuclear criticality safety depends upon control of neutron moderation, there shall be assurance that the prescribed extent of moderation remains unchanged or that, if a credible change occurs, the reactivity of the system remains below acceptable subcritical limits. Such assurance shall include consideration of all credible accidents involving any moderator or combination of moderators.

5.6.3.5.2 Consideration of interstitial moderation. Interstitial moderation shall be considered whenever such moderation is credible and shall be evaluated and controlled as in section 5.6.3.5.1.

5.6.3.5.3 Consideration of non-aqueous moderation. If moderators more effective than water may be present, their effects shall be considered and controlled.

5.6.3.5.4 Installed fire protection systems. In and of itself, the activation of installed fire protection systems shall not be capable of causing an criticality accident. If nuclear criticality safety considerations preclude the use of water sprinkler systems, other fire control measures should be utilized.

5.6.3.5.5 Exclusion of moderating materials. When moderation control is employed, enclosures (e.g., gloveboxes), material transport (e.g., trucks), and material transfer systems (e.g., conveyor lines) shall be designed such that moderating material in excess of established limits cannot be added accidentally to otherwise safe enclosures or systems.

5.6.3.6 Reflection control. Reflection control provides restrictions on the quantity, composition, and configuration of hydrogenous or other effective neutron reflecting materials in proximity to fissionable material.

5.6.3.6.1 Assumptions about neutron reflection. Nuclear criticality safety limits shall be based on full water reflection unless actual reflection is more reactive than water, or unless reflection is controlled, or it is not credible to achieve full reflection. Both normal operating conditions and credible accident conditions shall be considered.

5.6.3.6.2 Avoidance of reflection control. In general, reflection controls based on limiting personnel access to a system to maintain nuclear criticality safety should be avoided. In those few cases where reflection controls are needed that are based on limiting personnel access to a system, the INCSRC should review and concur with such limits on a case-by-case basis.

5.6.3.6.3 Use of water in fire fighting. Efforts shall be made, to the extent practical, not to limit fire fighters use of water. If the use of water is permissible for fire fighters, consideration shall be given to loss of spacing control caused by the force of the water stream in addition to change in reflection and moderation.

5.6.3.7 Mass control. Mass controls provide restrictions on the quantity of fissionable material permitted in individual units, in work areas, in a total configuration, or in the total number of units.

5.6.3.7.1 Over-batching. For operations depending upon mass controls, where the contained volume does not automatically limit the contents to a safe mass or less, multiple batching, or over-batching, shall be controlled to prevent unsafe accumulations.

5.6.3.7.2 Double batching. In areas where double batching is credible, minimum safety margins shall include consideration of such double batching.

5.6.3.7.3 Material form. If the determination of a mass limit assumes fissionable material in a physical or chemical form, it shall be shown that the change to a more reactive state, such as precipitation from a solution, freezing, or transfer to a second phase is unlikely before the change may be considered a contingency.

5.6.3.8 Volume control. Volume controls provide restrictions on the fissionable material volume, container volume, or vessel volume (may be specific to fissionable material composition).

5.6.3.8.1 Volumetric limits. Volumetric safety limits shall be based on the minimum volume required to sustain a nuclear fission chain reaction for the given fissionable material and composition. The minimum critical volume shall be that associated with the worst credible process conditions that may exist within the system, including consideration of system interactions with other process systems and the environment.

5.6.3.9 Enrichment or isotopic control. Enrichment controls provide restrictions on the maximum fraction of fissile or fissible nuclide (usually expressed as weight percent) for a fissionable element such as U or Pu. Operations depending upon such control shall have their nuclear criticality safety limits based upon the credible enrichment or isotopic composition that yields the maximum infinite medium multiplication factor, k_∞. The operational basis for the assumed isotopic composition or enrichment shall be documented as part of the NCSA to provide the validated bases for maximum k_∞.

5.6.4 Graded Approach to NCSAs and NCSEs. A graded approach to the performance of nuclear criticality safety analyses (NCSA) and the supportive nuclear criticality safety evaluations (NCSE) should be exercised. A NCSA is a documented analysis showing the subcriticality (i.e., the NCSE) and safety of discrete, basic facility operations or equipment involving the handling, processing, or storage of fissionable material under normal operational conditions and credible abnormal conditions (contingencies). The primary purpose of an NCSA is to document the basis of nuclear criticality safety (NCS) controls, engineered features, and related operating limits necessary to ensure that an acceptable margin of subcriticality and safety is maintained. A graded approach to the performance of nuclear criticality safety analyses acknowledges that different levels of effort and documentation are appropriate for different complexities of facility fissionable material operations (i.e., handling, processing, and storing) and the associated methods and controls applied to maintain subcriticality and safety.

The classification of facility complexity and levels of analyses and evaluations to be performed should be determined at an organizational level independent of facility operations or production (e.g., the safety organization reporting to the installation/facility manager). This determination should be based upon the technical judgment of a nuclear criticality safety specialist having at least the qualifications described in footnote 3 of Table 5.6.4.4.

5.6.4.1 Levels of analyses and evaluations. Levels of analyses or evaluations range in effort from simple references -- to common engineering and safety judgment and to national consensus standard subcritical values (e.g., 450g ^{239}Pu) using a highly reliable control on allowed facility fissionable material mass -- to a complicated validated computation of neutron interacting arrays of dissimilar systems involving materials having variable nuclear parameters and numerous administrative/procedural and physical controls benefitting from probabilistic risk analyses. Three levels of analysis and evaluation are considered: Levels A, B, and C. Level A analyses and evaluations may be performed for facilities having fissionable material inventories and operational conditions that will remain within the envelope of conditions specified for subcritical values within national consensus standards. Level B analyses and evaluations are performed for facilities having fissionable material inventories or operational conditions that exceed the envelope of national consensus standard subcritical values but have fissionable material inventories and operational conditions that may be analyzed to be safely subcritical by reference to commonly accepted and used handbook or safety guide values. Where these values are not based directly on experimental data, such as tables or figures based solely on calculated values, they should be confirmed from two independent sources. Level C analyses and evaluations are typically performed for fissionable material inventories and operational conditions that cannot be addressed with national consensus standards or handbook values. Level C analyses and evaluations may involve the application of computational techniques requiring computer program documentation, verification, validation, and user qualification.

In all cases, it shall be shown that all normal and credible abnormal operational conditions and contingencies remain within the envelope of the specified subcritical process and nuclear parameters. All physical and administrative controls used for ensuring the subcritical values shall be clearly identified. The reliabilities of the controls shall be described to be acceptable. The single failure of any one of the controls shall be shown not to result in a criticality accident. By order of preference, referable facility historic data, industrially accepted guidance, and, lastly, experienced engineering judgment about human and equipment reliability shall be used to defend the reliability of nuclear criticality safety controls.

5.6.4.1.1 Level A. Level A evaluations are performed by direct reference to national consensus standard subcritical values. Such references include ANSI/ANS-8.1-1983,R88, *Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors*, and ANSI/ANS-8.15-1981,R87, *Nuclear Criticality Control of Special Actinide Elements*. Though no additional verification of the subcritical values are required, a clear comparative evaluation of the operation being evaluated shall be given along with the basis of safety.

5.6.4.1.2 Level B. Level B evaluations are performed with referenced values derived from published handbooks, safety guide subcritical values, or criticality data. Such well known references include, but are not limited to, LA-10860-MS, *Critical Dimensions of Systems Containing ^{235}U, ^{239}Pu, and ^{233}U* (section 2.3.2.9 of this standard); NUREG/CR-0095 ORNL/NUREG/CSD-6, *Nuclear Safely Guide TID-7016 Revision 2* (section 2.3.2.10 of this standard); and ARH-600, *Criticality Handbook*. The referenced values shall be based directly on experimental data or shall be verified to be consistent with independent handbooks or safety guide subcritical values or validated computational techniques. Level B analyses shall be based on critical data only after appropriate margins of subcriticality have been applied to the critical values. The use of unpublished experimental logbook data requires comparison with a Level C evaluation as described in section 5.6.4.1.3. The identification of and reliability of controls shall be as described in section 5.6.4.1 above.

5.6.4.1.3 Level C. Level C analyses are performed by the use of a validated computational technique. Examples include ORNL/NUREG/CSD-2/VI/R2, *KENO-Va, An Improved Monte Carlo Criticality Program with Supergrouping*; LA-7396-M, Rev.2, *MCNP, A General Monte Carlo Code for Neutron and Photon Transport*; and BNFL SAG/80/P29, *Criticality Assessment Using the Limiting Surface Density (NB_n^2) Method and Examples of Application*. Acceptable margins of subcriticality and range of applicability for the chosen evaluation technique shall have been determined and documented for use in criticality safety evaluations. No single computational result shall be used for determining the subcriticality and safety of an operation. Rather, multiple results showing trends and computational reliability will be used. The use of Level C analyses shall be in conformance with ASME NQA-2 requirements. The identification of and reliability of controls shall be as described in section 5.6.4.1 above.

5.6.4.2 Complexities of facility fissionable material operations. Complexities of facility fissionable material operations range from single operations having less than a significant quantity of fissionable material to multiple operations having large quantities of fissionable materials processed in multipurpose facilities with many types of interfacing operations and support activities. Four classes of complexities are defined as follows:

5.6.4.2.1 Class I. Class I facility operations have less than significant quantities of fissionable materials presenting no significant risk of criticality within item control areas or material balance areas. Nuclear criticality safety is applied through facility nuclear material possession and accountability limits.

5.6.4.2.2 Class II. Class II facility operations have significant quantities of fissionable materials and have operations limited to repetitive and routine activities. No significant quantities of fissionable material wastes are generated in Class II facility operations. Nuclear criticality safety is applied with physical barriers such as spent or fresh fuel storage racks and single item handling devices. The fissionable material operations are performed in control areas that effectively preclude neutron interaction among items. Examples include, but are not limited to, fuel element examination operations, fissionable material item packaging, and storing.

5.6.4.2.3 Class III. Class III facility operations have significant quantities of fissionable materials and perform operations that influence other fissionable material operations within the facility. Examples include, but are not limited to, analytical laboratories, foundries, machine shops, dimensional inspection shops, nondestructive testing shops, etc. that exchange materials among the various operations. Significant quantities of fissionable material wastes in solid and liquid forms are generated and collected but are not processed to finally recovered forms. The fissionable material operations are performed in effectively non-neutron interacting item control areas and material balance areas.

5.6.4.2.4 Class IV. Class IV facility operations are multipurpose and include all of the characteristics of a Class III facility but with the addition of complex operations including solution, waste recovery, waste processing, and decontamination and decommissioning operations. Additionally, the fissionable material operations may be performed in neutron interacting item control areas and material balance areas.

5.6.4.3 Analysis Content. Despite the level of effort and documentation of evaluations and analyses and the complexity of an operation, the same fundamental elements shall be included and identified in the safety analyses for each discrete operation within the facility. The safety analyses shall be retained in accordance with section 2.1.2. These elements include the following:

5.6.4.3.1 Operational description. Using verified as-built sketches, drawings, or flow diagrams of the equipment, portable containers, and of processes and facilities, the description of the intended fissionable material operation under analysis shall be provided for which the hazard of criticality exists. Care should be exercised to identify, for additional analysis, ancillary support equipment or activities that may require independent safety analyses (e.g., vacuum producers, nonfissionable material feed chemical make-up and supply, compressed gas/air, waste collection, ventilation, transportation, neutron interaction among other fissionable material systems, etc.) and that may affect, or be affected by, the operation under consideration. The description shall be of sufficient detail to permit independent evaluations and safety analyses of the operation.

5.6.4.3.2 Fissionable material forms. Bounding descriptions of the chemical and physical form(s) of fissionable material in the operation shall be provided, including isotopic content, resulting concentrations, densities, degrees of neutron moderation, degrees of neutron interaction and reflection considered, and the physicochemical stability of the fissionable material in the anticipated normal or abnormal operating environment.

5.6.4.3.3 Credible operating condition changes. This includes the description of the normal and abnormal credible changes in operating conditions that could alter a nuclear parameter (i.e., geometry/volume, spacing/interaction, neutron absorption, concentration/density, mass, moderation, reflection, and enrichment) beyond intended operating conditions. The description shall include a characterization of any resultant conditions, masses, forms, materials, etc. adversely affecting subcriticality and safety.

5.6.4.3.4 Analysis of accident scenarios. This includes the identification of event sequences leading to credible nuclear criticality accident scenarios (a single scenario probability exceeding a frequency of 1×10^{-6} per year) and associated consequences to workers, the public, and facilities. Bases shall be specified if no credible accident scenarios can be determined.

5.6.4.3.5 Need for CAS or CDS. A review for the need and placement of a nuclear criticality accident alarm or detection system shall be provided. Alarm and detector coverage shall be provided as necessary, or a reference supplied that indicates fulfillment of the alarm or detector need and placement (see section 5.4).

5.6.4.3.6 Safety controls description. The description of the passive and active safety controls that are part of the operation shall be identified and shall include the intended administratively or physically controlled value(s) for each of the nuclear parameters. If a specific nuclear parameter does not affect the operation, a short justification for excluding the nuclear parameter from the analysis shall be provided. Technical practices and measurement control programs used for ensuring the reliability of safety controls shall be provided.

5.6.4.3.7 NCSE summary. The summary description of the validated technical nuclear criticality safety evaluations (computational or comparative) showing the subcriticality of the operation under normal and abnormal conditions should be provided. The safety evaluation shall identify and consider interactions with any other fissionable material operations within the facility.

5.6.4.4 Performance of NCSAs and NCSEs. As indicated above, a "Graded Approach" acknowledges that different levels of effort and documentation are appropriate for different complexities of facility fissionable material operations. The gradation of levels of effort and of documentation and the complexities of operations may be seen as a two-dimensional matrix, as shown in Table 5.6.4.4-1, which is used for grading the approach and resources required for performing the NCSA and NCSE. The table footnotes provide explanations about the resources that are numbered 1 through 4. A peer review is to be conducted for any NCS analysis and associated evaluation.

Table 5.6.4.4-1. Resources required for performance of the NCSA and NCSE.

	Facility Complexity			
Analysis Effort	Class I	Class II	Class III	Class IV
Level A	1	2	2	2
Level B	2	2 or 3	3	3
Level C	--	3 or 4	4	4

Legend: Level of Effort and Personnel Qualifications

1. Operations Supervision.
2. Qualified Nuclear Criticality Safety Specialist having experience interpreting safety guides and critical data references, in conjunction with an experienced process/operations engineer who is familiar with operational process, equipment, and facility normal and abnormal conditions.
3. Qualified Nuclear Criticality Safety Specialist having operational and process knowledge and experience interpreting safety guides and critical data references, in conjunction with an experienced process/operations engineer who is familiar with operational process, equipment, and facility normal and abnormal conditions.
4. Qualified Nuclear Criticality Safety Specialist having operational and process knowledge, experience interpreting safety guides and critical data references, and computational validation and analysis experience, in conjunction with an experienced process/operations engineer who is familiar with operational process, equipment, and facility normal and abnormal conditions.

5.6.4.5 Results of the Graded Approach. As indicated by the combination of complexities of operations with levels of effort required for analyses or evaluations, as described in sections 5.6.4.1

and 5.6.4.2 and shown in Table 5.6.4.4 above, an NCS analysis or evaluation may result in a seemingly minor safety document for Class I - Level A type analyses or evaluations, whereas a Class IV - Level C analysis or evaluation may result in a rather prodigious report. Additionally, the required resources can be quite variable. In all cases, the safety analysis shall contain all of the elements described in section 5.6.4.3 that are relevant to the operation, or appropriate NCS analyses or evaluations that supply these elements may be referenced. More in-depth descriptions and examples of such analyses and evaluations are provided in sections 5.7, 5.8, and 5.9.